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AD-A276 400



NRL Memorandum Report 6785

**Design of an Electron Gun for a 280 GHz
Induced-Resonance-Electron-Cyclotron
(IREC) Maser Experiment***

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**Work Supported by the Office of Naval Research*

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 1991 February 16		3. REPORT TYPE AND DATES COVERED Interim
4. TITLE AND SUBTITLE Design of an Electron Gun for a 280 GHz Induced-Resonance-Electron-Cyclotron (IREC) Maser Experiment			5. FUNDING NUMBERS 47-3046-01 ONR	
6. AUTHOR(S) R. B. McCowan, R. A. Pendleton [†] and A. W. Fliflet				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory Washington, DC 20375-5000			8. PERFORMING ORGANIZATION REPORT NUMBER NRL Memorandum Report 6785	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Arlington, VA 22217			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES *Work Supported by the Office of Naval Research [†] Varian Assoc., Inc., Palo Alto, CA				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A 280 GHz, thermionic electron gun for induced-resonance-electron-cyclotron (IREC) maser applications have been designed. The 500 kV, 200 A MIG type electron gun has a curved emitting surface designed to compensate for radial electric field gradients across the cathode, and will produce an electron beam with $v_{\perp}/v_z \approx 0.5$ and $\Delta v_z/v_z < 1\%$. The gun is also capable of producing an electron beam suitable for a 250 kV quasioptical gyrotron.				
14. SUBJECT TERMS Electron-Gun IREC maser			15. NUMBER OF PAGES 21	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED		18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR

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DESIGN OF AN ELECTRON GUN FOR A 280 GHz INDUCED-RESONANCE-ELECTRON-CYCLOTRON (IREC) MASER EXPERIMENT*

I. Introduction

The induced resonance electron cyclotron (IREC) maser¹ is a promising source of high power radiation in the 100 GHz to 500 GHz frequency range that may impact the requirements of advanced systems for applications such as high-resolution radar. The IREC maser can provide mm and sub-mm radiation in the first electron cyclotron harmonic using currently available magnet technology. The IREC maser eliminates the problem of the low frequency oscillation from the CARM by providing a quasi-optical (QO) cavity structure that will not support the low frequency modes. In addition, in the IREC maser, as in the QO gyrotron, the radiation is naturally decoupled from the electron beam. Since the IREC maser is an oscillator, it requires no driver source, a strong advantage at frequencies over 100 GHz.

This paper presents the design of an electron gun to provide the electron beam for an IREC maser experiment. The IREC maser experiment requires a 500 kV, 100-200 A annular electron beam with the ratio of transverse velocity to axial velocity (α) adjustable between 0.3 and 0.6, and $\Delta v_z/v_z$ less than 3%. A magnetron-injection-gun (MIG) design was chosen for the experiment for two reasons. First, in a given beam transport tube, an annular beam can carry more beam current than can a solid (pencil) beam. Second, and more important, the MIG can be analyzed with two-dimensional gun design tools; with existing 2D gun design codes space charge can be modelled effectively. A gun that relies on 3 dimensional effects, such as a Pierce-wiggler configuration, can not be as thoroughly analyzed. Since any Doppler-shifted cyclotron maser requires a high quality electron beam, the existence of the necessary design tools is important.

In large, high power electron guns, the electric field is bound to be nonuniform over the emitting surface. A main feature of the electron gun design described in this paper is the curved emitter, which is used to compensate for the nonuniformity in the electric field.

Manuscript approved November 28, 1990.

*Work Supported by the Office of Naval Research

The only high-voltage, high-power MIG to be built and tested to this date is the University of Maryland's gyro-klystron gun². By keeping the high voltage structure similar to University of Maryland's gun, the design of the overall gun was reduced to mainly the design of the cathode electrode shapes, decreasing overall costs and procurement time, while diminishing the risk of high-voltage failure.

II. Requirements on the Beam and Gun

In order that the 100 MW, 500 kV IREC maser operate with high efficiency, the electron gun must provide an electron beam with an axial velocity spread smaller than 3%. In order that the experiment have wide latitude in operating parameters, the gun should be designed to produce an electron beam with low velocity spread over a wide range of currents and velocity pitch ratios. Depending on the resonator configuration, the IREC maser can have start currents as low as 5-10 A; the primary goal of this design is to produce a high quality electron beam with beam α adjustable between 0.3 and 0.6 for any current up to 200A.

The velocity spread in an electron beam comes from a number of sources. In the design of this gun we will consider the contributions of the shape of the electrode surfaces, the temperature of the cathode, and the surface roughness of the cathode. The majority of this work is the optimization of the shape of electrode surfaces with respect to velocity spread. Once the velocity spread due to electrode-surface shapes is minimized, the effects of surface roughness and temperature of the cathode are analyzed.

A useful starting point for the design of a high-power MIG is the set of adiabatic scaling equations derived by Baird and Lawson³ and used for the preliminary design studies for the University of Maryland's 500 kV gyro-klystron electron gun². These equations calculate the initial transverse momentum of the electrons from the electric and magnetic fields at the cathode and the cathode angle and radius. The electron beam is then scaled adiabatically into the interaction region. The gun design parameters from the adiabatic scaling studies are shown in Table 1.

Beam Voltage	500 kV
Intermediate anode voltage	165 kV
Beam Current	100 A
Magnetic Field	50 kG
Guiding Center Radius	0.5 cm
Beam α	0.5
Cathode Angle	20°
Cathode Radius	3 cm
Maximum electric field	50 kV/cm

Table 1. The design parameters for the scaling studies for the IREC maser gun.

The electric field strengths in the adiabatic trade-off equations should be kept less than 50% of the maximum field strengths for the final design; our gradient calculations show that the peak electric field strength on the curved surface required to produce a realistic gun geometry is approximately double that predicted by a planar geometry with the same anode-cathode gap.

Because of the required wide range of operating parameters, a double-anode gun design was chosen. The presence of the control anode allows change of the beam α without affecting the current or beam radius. A double-anode design with the parameters shown in Table 1. and a nominal control anode voltage of 165 kV was chosen. An electron trajectory code⁴ was used to obtain the ray trajectories. The trajectory code results revealed the weakest point of the adiabatic trade-off equations for high-power gun design. The adiabatic trade-off equations assume a uniform electric field across the emitting region. In practice, however, the cathode electric fields are likely to be quite nonuniform over emitters large enough to keep the beam loading at reasonable levels ($J_{\text{cath}} < 8\text{-}10 \text{ A/cm}^2$).

In our gun, this nonuniformity produces a variation in α across the beam from 0.5 to 0.75, clearly unacceptable for efficient IREC maser operation (see Figure 1). Lawson² saw a similar effect when designing the University of Maryland's gyro-klystron gun. For the gyro-klystron gun, the electric field gradient across the emitter was compensated downstream by space charge depression across the beam, which reduces the axial velocity of the inner portions of the beam and therefore reduces the axial velocity spread. Because the space charge is due to beam current, this approach leads to an electron gun for which beam quality is a sensitive function of beam current,

and is therefore unsuitable for the IREC maser experiment, which requires operation at both high and low beam currents.

In order to produce a high quality electron beam over a wide range of currents, the gradients across the emitter were offset by contouring the emitting surface. With a concave cathode the portion of the beam emitted in the higher-electric-field region is emitted more nearly parallel to the magnetic field than that portion emitted in the lower-electric-field region, keeping the initial transverse momentum approximately constant across the emitter. Since curving the cathode changes the electric field in the cathode region, this approach involves a number of iterations of an electron gun code. With sufficient refinement of the cathode shape, however, a sufficiently constant initial transverse momentum can be obtained.

We chose to keep the inner portion of the emitter at approximately 20° in order to provide laminar electron flow near the cathode surface. This geometry is shown in Figure 2. As will be shown below, the electron trajectories are laminar nearly all the way to the cavity. A geometry of this type can provide a high quality electron beam over a wide range of currents and α 's.

A high compression ratio is required for this MIG gun for two reasons. The radius of the electron beam in the interaction region must be small because the radiation profile in the cavity is only 1 cm diameter, while the emitter must be large in order to keep the beam cathode loading at a reasonable level. In addition, the electric field on the cathode focus surfaces must be kept below 100 kV/cm; this requirement reduces the amount of transverse momentum the electrons can receive at the cathode. The limited transverse electric field, coupled with the emitter angle needed for laminar flow increases the amount of magnetic compression required for any given beam α .

III. Electron Trajectory Simulations

The important dimensions and parameters for the trajectory simulations are shown in Table 2. Trajectory simulations were performed both at the Naval Research Laboratory and at Varian Associates. These simulations differ by no more than a few percent for any given run. The Varian rectangular mesh code generally predicts better performance than does the NRL square mesh code. The simulations presented here are from the NRL code.

Initial cathode angle	18°
Emitter radius of curvature	3.5 cm.
Anode-cathode gap	5.5 cm
Cathode magnetic field	0.12 T
Magnetic field compression ratio	50
Average cathode electric field	80 kV/cm

Table 2. Trajectory simulation parameters.

Table 3 shows the beam parameters for operation of the gun at 100 A, a control anode voltage of 175 kV, and no magnetic field provided except the fringe fields of the 60 kG, 20 cm-ID, 30 cm-long Helmholtz-like coil that provides the magnetic field for the oscillator cavity. The emitting surface of the gun is approximately 70 cm from the center of the Helmholtz-like coil. For this set of parameters the axial velocity spread is approximately 0.5%. Figure 3 shows the boundaries for the trajectory run for this configuration, and Figure 4 shows the beam α in the interaction region as a function of guiding center radius.

Voltage	500 kV
Current	100 A
Control anode voltage	175 kV
Cavity magnetic field	60 kG
β_z	0.791
$\Delta\beta_z/\beta_z$	0.525%
α	0.435
$\Delta\alpha/\alpha$	3.24%

Table 3. The beam parameters for the electron gun design at 100 A, with a control anode voltage of 175 kV.

A wide range of trajectory runs were performed in order to assure a sufficient latitude in gun operation parameters. The control anode can be run from 140 kV to 185 kV. At voltages outside this range, the field strengths on the cathode or anode exceed 100 kV/cm, the limit for reliable operation. Beam current was run from 0 A to 200 A, and a magnetic field trim coil was designed to provide even greater flexibility. The coil can provide magnetic fields of up to 300 G at the emitter. It has a 24"

diameter and is assumed to operate with current densities not exceeding 300 A/cm². These coil current densities are easily achieved using water-cooled magnets.

Results of the simulations for 100 A of beam current are shown in Figures 5 and 6. Figure 5 shows beam α as a function of the axial magnetic field at the cathode for control anode voltages of 165 kV, 175 kV, and 185 kV. Positive trim current increases the magnetic field at the cathode, reducing both the initial transverse momentum and the magnetic compression, and hence lowers the beam α . Accordingly, negative trim current results in increased α . Figure 6 plots axial velocity spread in percent as a function of α , and indicates that α 's up to 0.65 can be achieved with geometrical velocity spreads less than 1%, well within the requirements of the IREC maser. The wide range of beam α for which the beam has a low velocity spread is an important characteristic for IREC maser operation, and in addition gives a great deal of confidence in the flexibility of the gun design. Figures 5 and 6 also show that the trim coil can be used to vary beam α while keeping the control anode voltage within the limits set for reliable high voltage operation.

Figure 7 shows the results for the electron gun operated at 200 A of beam current. The axial velocity spread for a final beam α of 0.5 is under 1.5%, still within the requirements of the QO CARM design. At 200 A, space charge increases the axial velocity spread for lower control anode voltage. Lower velocity spread could be achieved for 200 A by increasing the control anode voltage above 185 kV, but the electric field stresses on the cathode will exceed the design goals for reliable high-voltage operation.

The IREC maser electron gun can also be operated as a high-voltage gun for a quasioptical gyrotron⁵. The magnetic field profile is similar to that in the IREC maser configuration, with the magnetic field being provided by a 5.0 T cross-bore superconducting magnet. Figure 8 presents the results of gun simulations in the quasioptical gyrotron configuration. By lowering the voltage from 500 kV to 250 kV while keeping the voltage between the cathode and the control anode at 180 kV, the beam α can exceed 1.2 with perpendicular velocity spreads less than 5% for currents less than 100 A. For current greater than 100 A the beam α is predicted to be near 1. Table 4 outlines the parameters of a proposed 250 kV quasioptical gyrotron using the IREC maser electron gun.

Frequency	~ 100 GHz
Gun voltage	≤ 250 kV
Beam current	≤ 150 A
Magnetic field compression ratio	50
Pulse length	1.2 μsec
Beam momentum pitch ratio	1-1.5
Resonator mirror diameter	9 cm
Mirror separation	58 cm
Output coupling	4.5%
Output power	>2 MW

Table 4. Parameters for the 250 kV quasioptical gyrotron experiment.

IV. The Effect of Cathode Temperature and Roughness

In addition to the velocity spread introduced by the geometrical shape of the cathode, the effects of cathode temperature and surface roughness will be considered. The analysis here is based on the results of Tsimring⁶.

The transverse velocity spread due to surface roughness is given by Tsimring:

$$\delta v_{\perp} = 1.6n \sqrt{\frac{r_0}{h_0} \left(1 + \frac{\pi^2}{4} \tan^2 \varphi \right)},$$

where φ is the angle between the emitter and the magnetic field, r_0 is the characteristic radius of the roughness, and is chosen to be 1 μm, h_0 is the height above the emitter surface of the first vertex of the trajectories, and n is a velocity reduction factor, which is 1 in our case. For the MIG gun at 150 Amps and a beam α of 0.5, δv_{\perp} is less than 3%, which corresponds to δv_z of approximately 0.7%.

The velocity spread due to the emitter temperature is given by

$$\delta v_{\perp} = 4 \sqrt{\frac{\bar{u}_e}{u_a} \left[\frac{d}{h_0} \left(1 + \frac{\pi^2}{4} \tan^2 \varphi \right) \right]},$$

where \bar{u}_e is the average electron energy at the emitter, u_a is the anode voltage, and d is the anode-cathode spacing. For operating parameters for our gun, the transverse velocity spread due to the cathode temperature is approximately 1%. This corresponds to an axial velocity spread of approximately 0.25%.

The total axial velocity spread of the electron beam is

$$(\delta v_z)_{total}^2 = (\delta v_z)_{thermal}^2 + (\delta v_z)_{roughness}^2 + (\delta v_z)_{geometry}^2 ,$$

which for 150 Amps at beam α of 0.5 is approximately 1.1%, well within the requirements for high efficiency operation of the IREC maser.

V. Conclusion

In this paper we have presented the properties of a high-power, relativistic MIG with a curved-emitter cathode. Using adiabatic scaling equations and electron trajectory codes, a 50-100 MW electron beam design is achieved for a 280 GHz quasi-optical CARM oscillator. The design is unique in its high voltage and high power capability and the curved emitting surface used to achieve a very low (less than 1%) axial velocity spread over a wide range of parameters. This gun has been delivered and will undergo high-voltage testing in the Fall, 1990.

VI. Acknowledgement

This work was supported by the Office of Naval Research.

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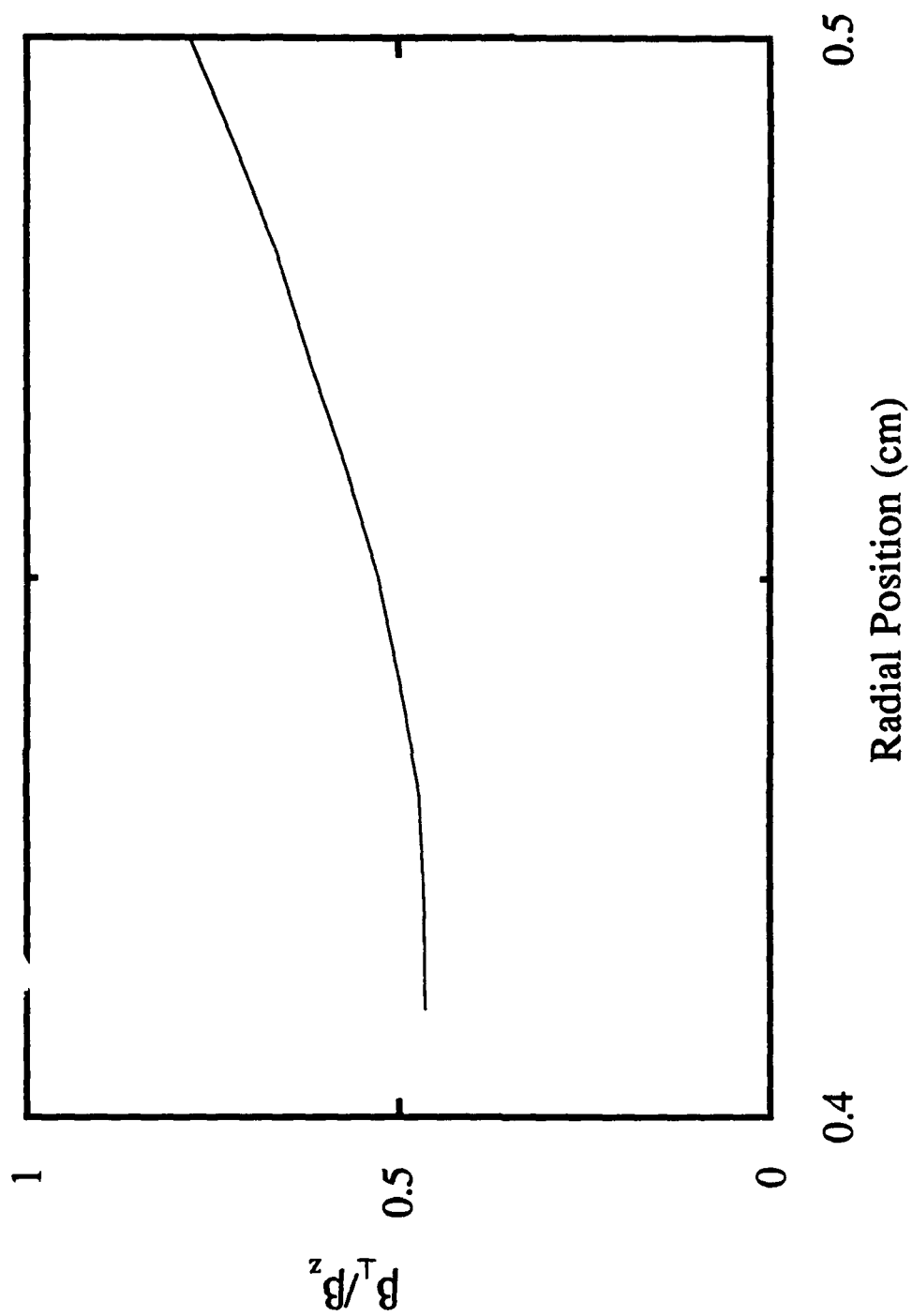


Fig. 1 — Electron beam α as a function of guiding center radius for a MIG gun with an uncurved cathode

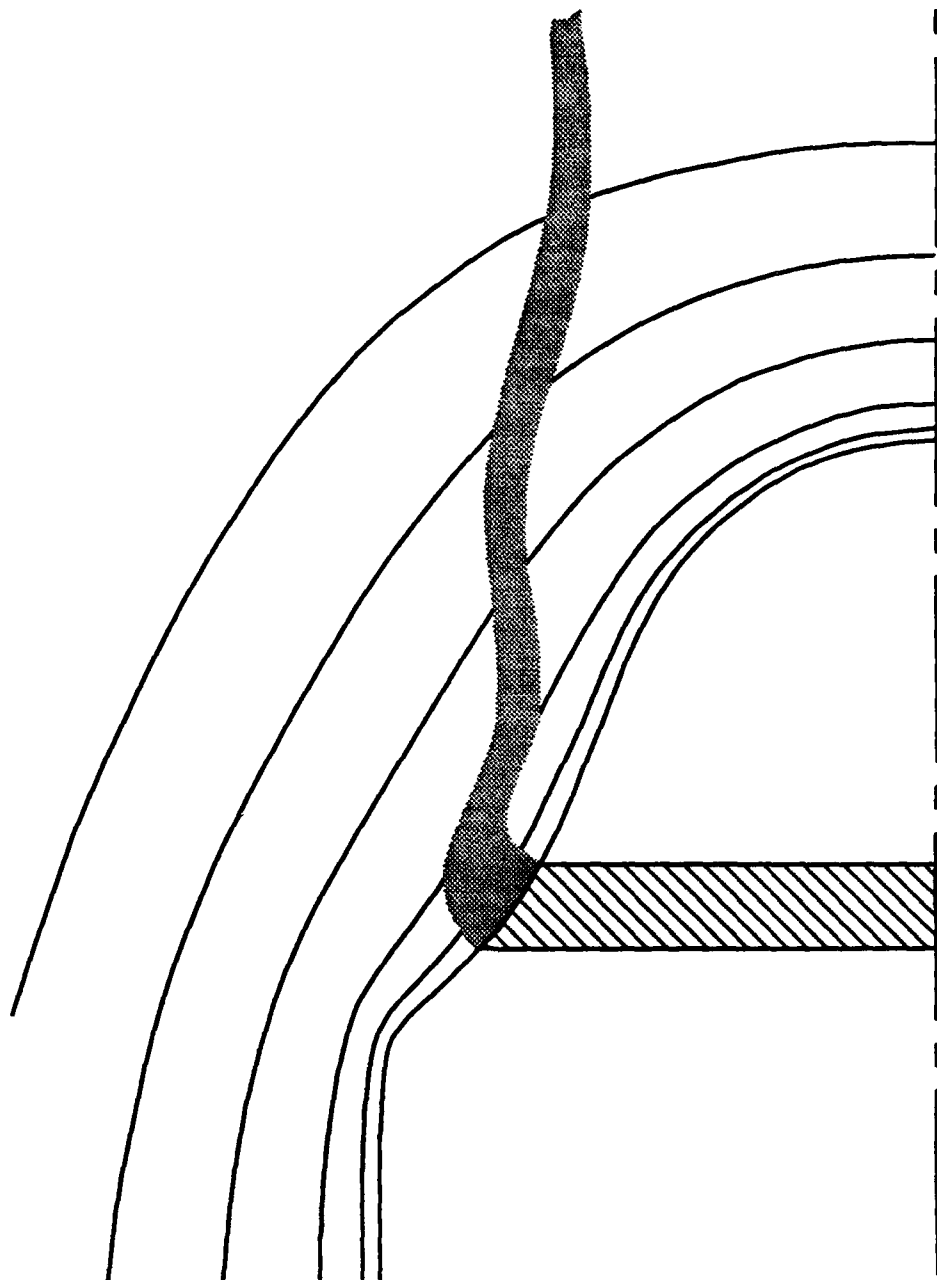


Fig. 2 — The Geometry at the emitter, illustrating the curvature of the cathode surface. The flow in this region is laminar

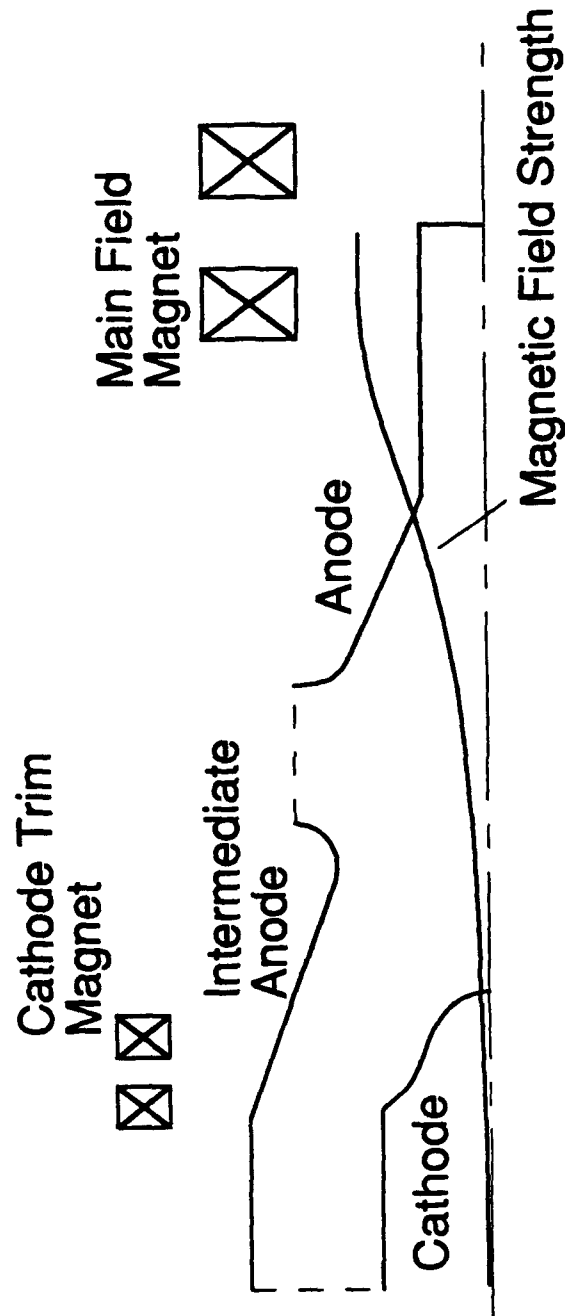


Fig. 3 — The boundaries for an electron trajectory code run for the IREC maser electron gun configuration

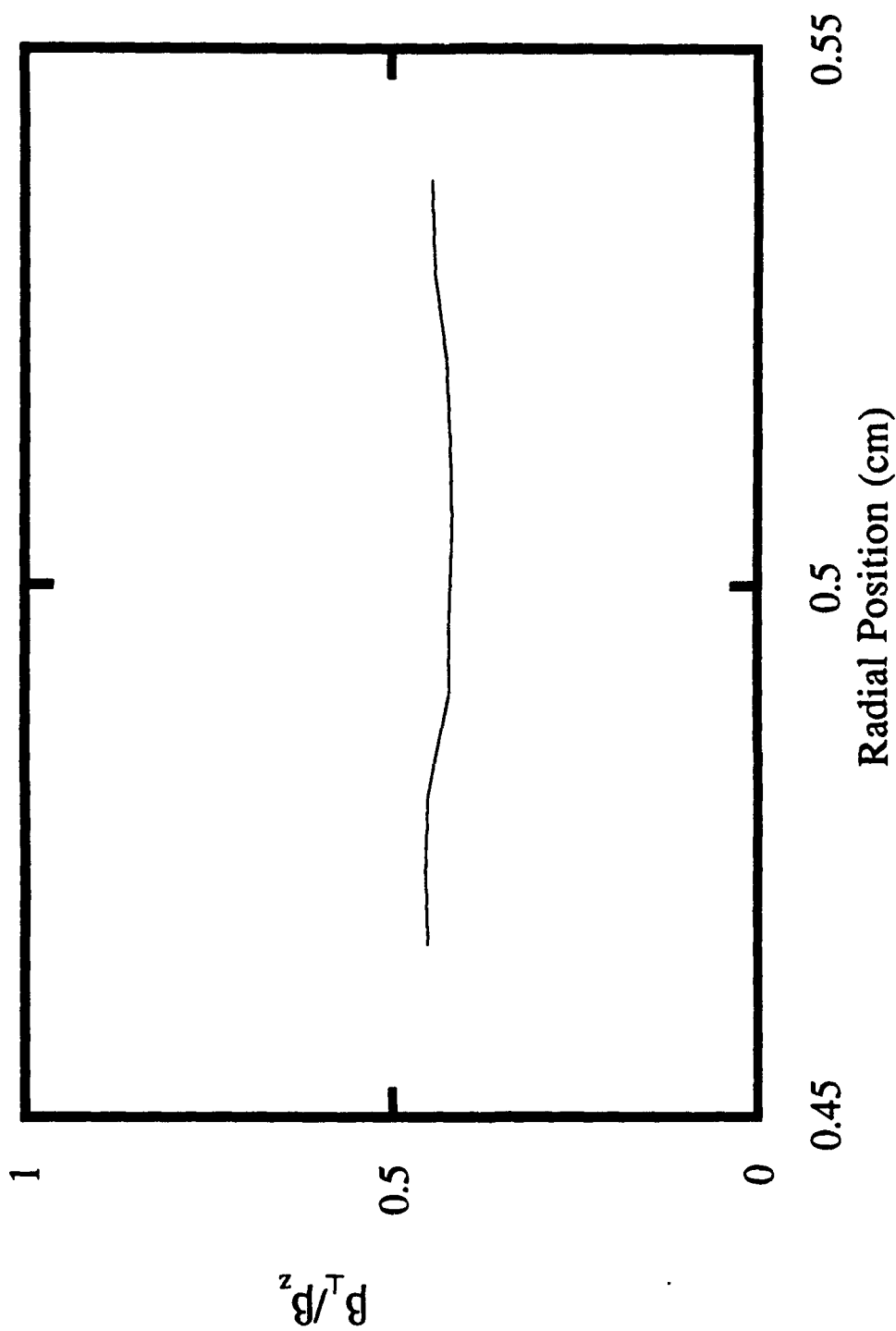


Fig. 4 -- Electron beam α as a function of guiding center radius for the curved-cathode MIG gun. The beam current is 100 A, and the control anode voltage is 175 kV.

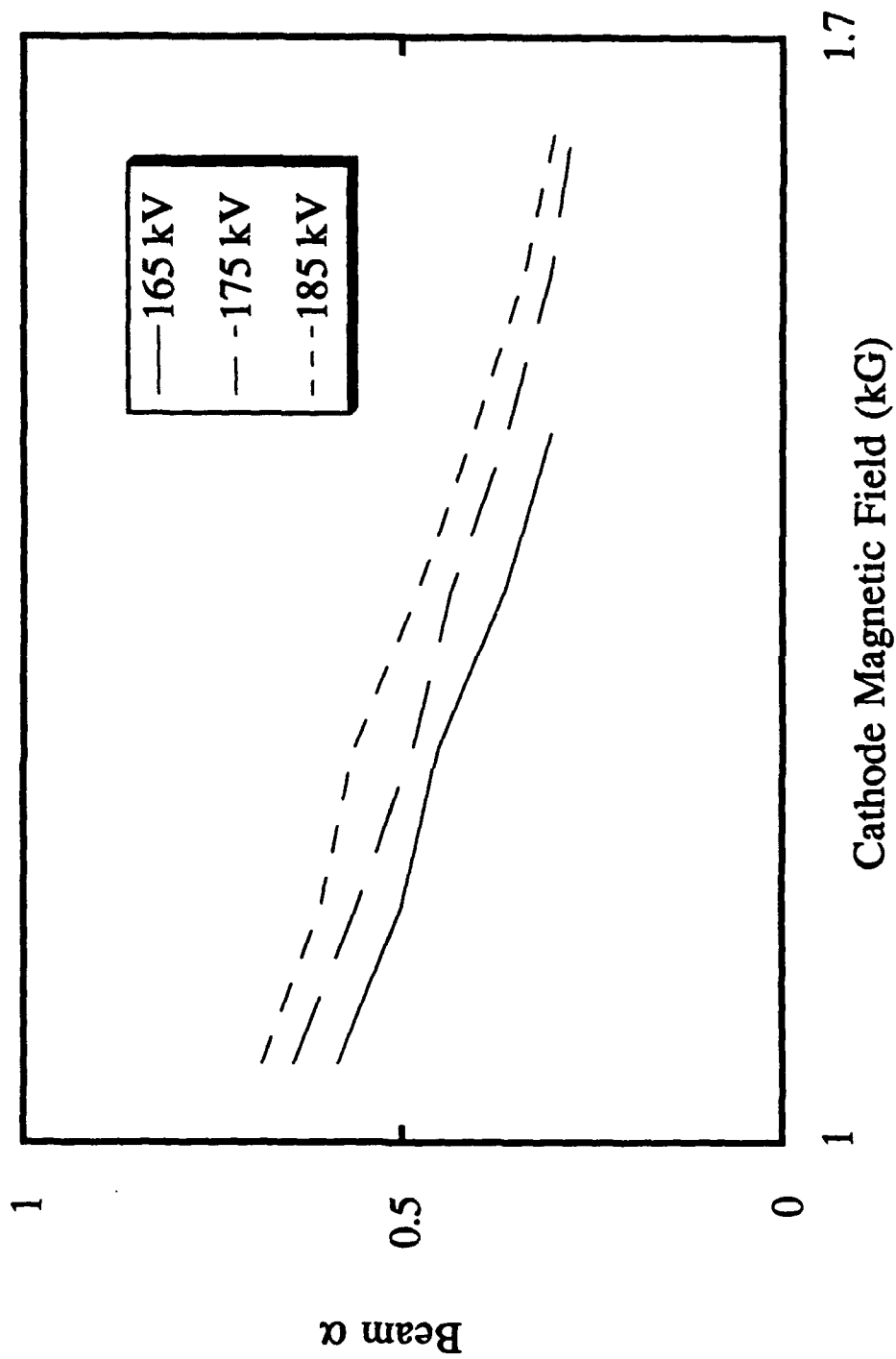


Fig. 5 — Average α as a function of cathode magnetic field for various control anode voltages

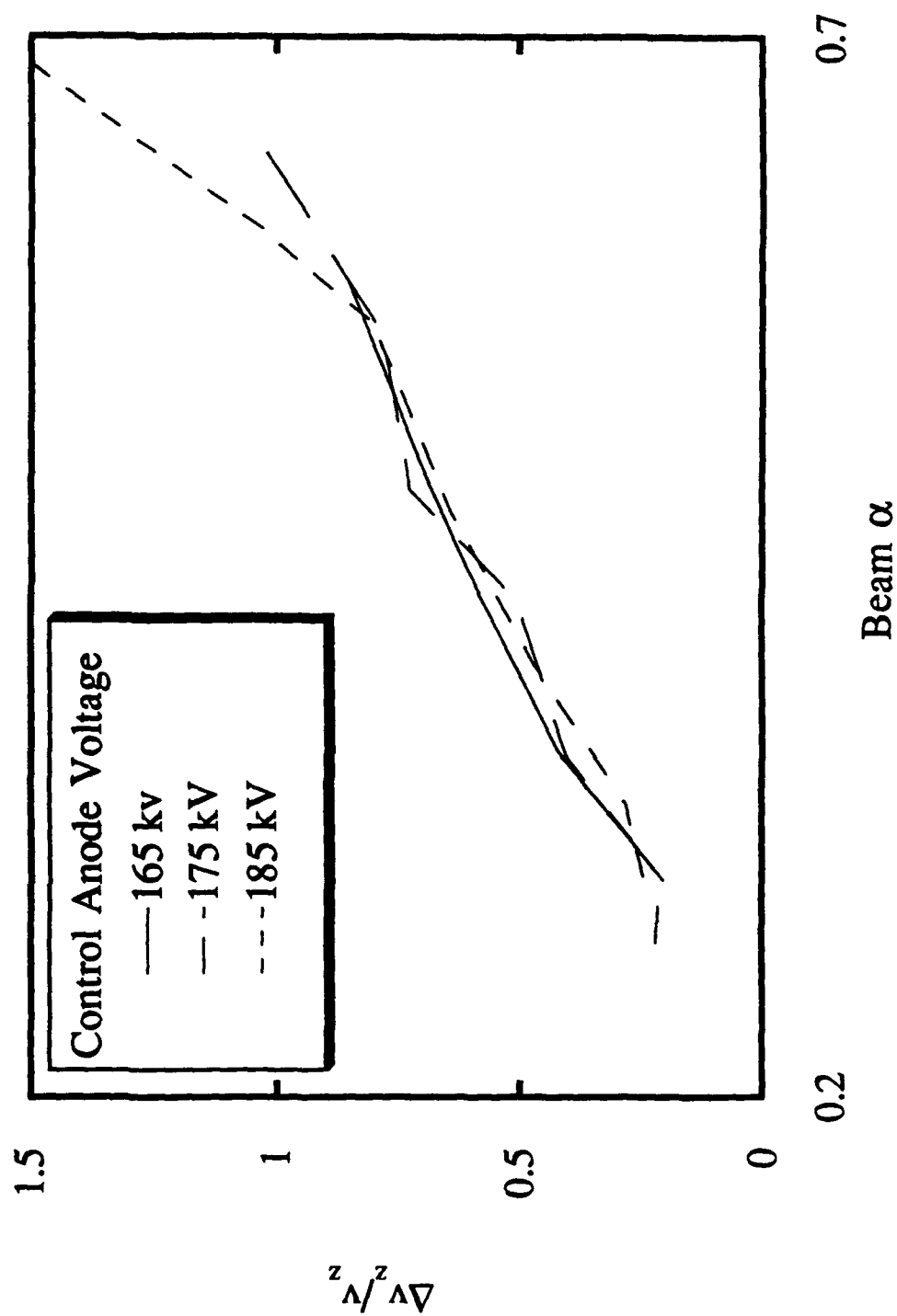


Fig. 6 — Axial velocity spread as a function of beam angle. $I_b = 100$ A

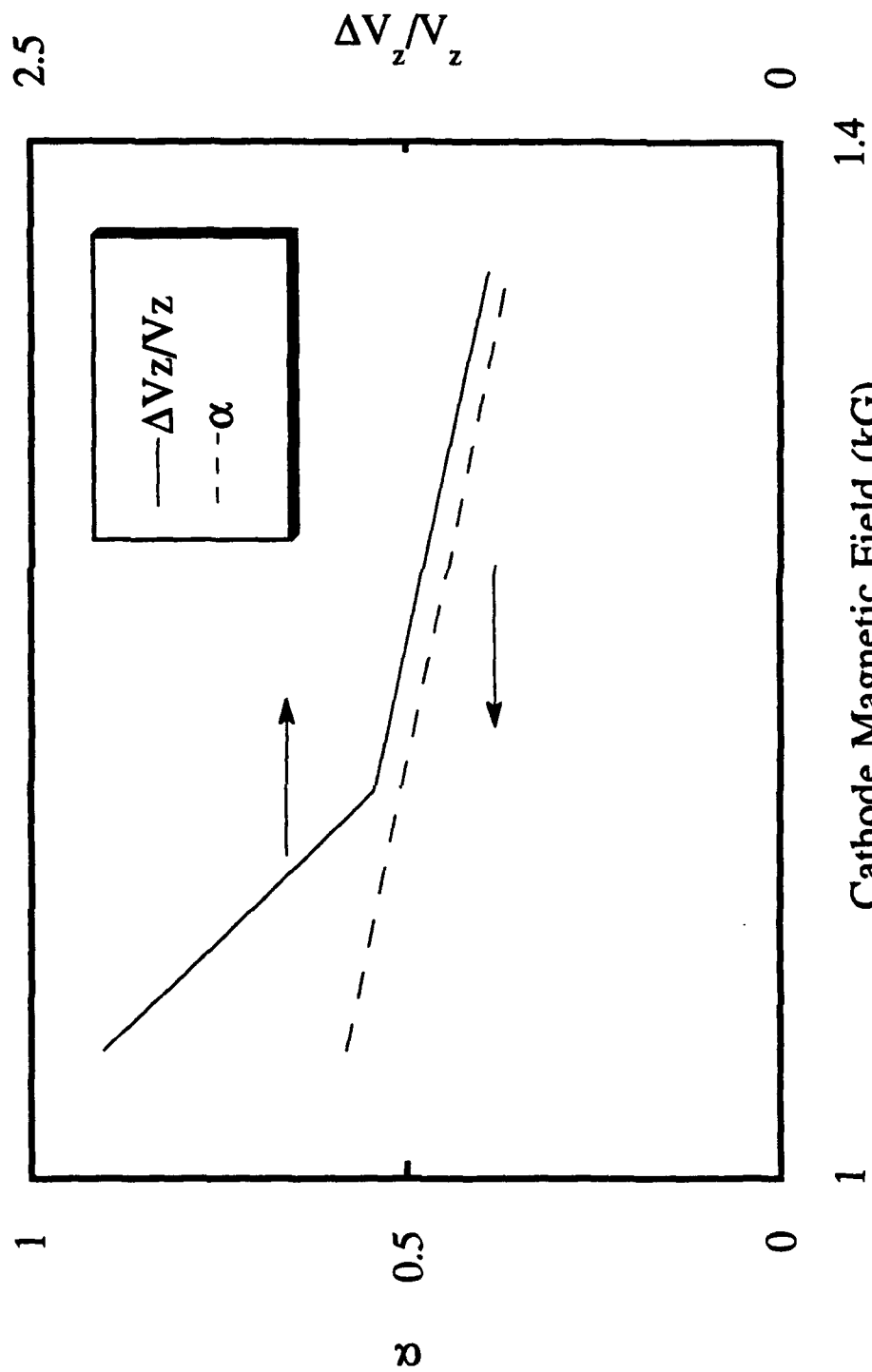


Fig. 7 — Beam alpha and axial velocity spread as a function of cathode magnetic field. The current is 200 A, and the control anode voltage is 185 kV.

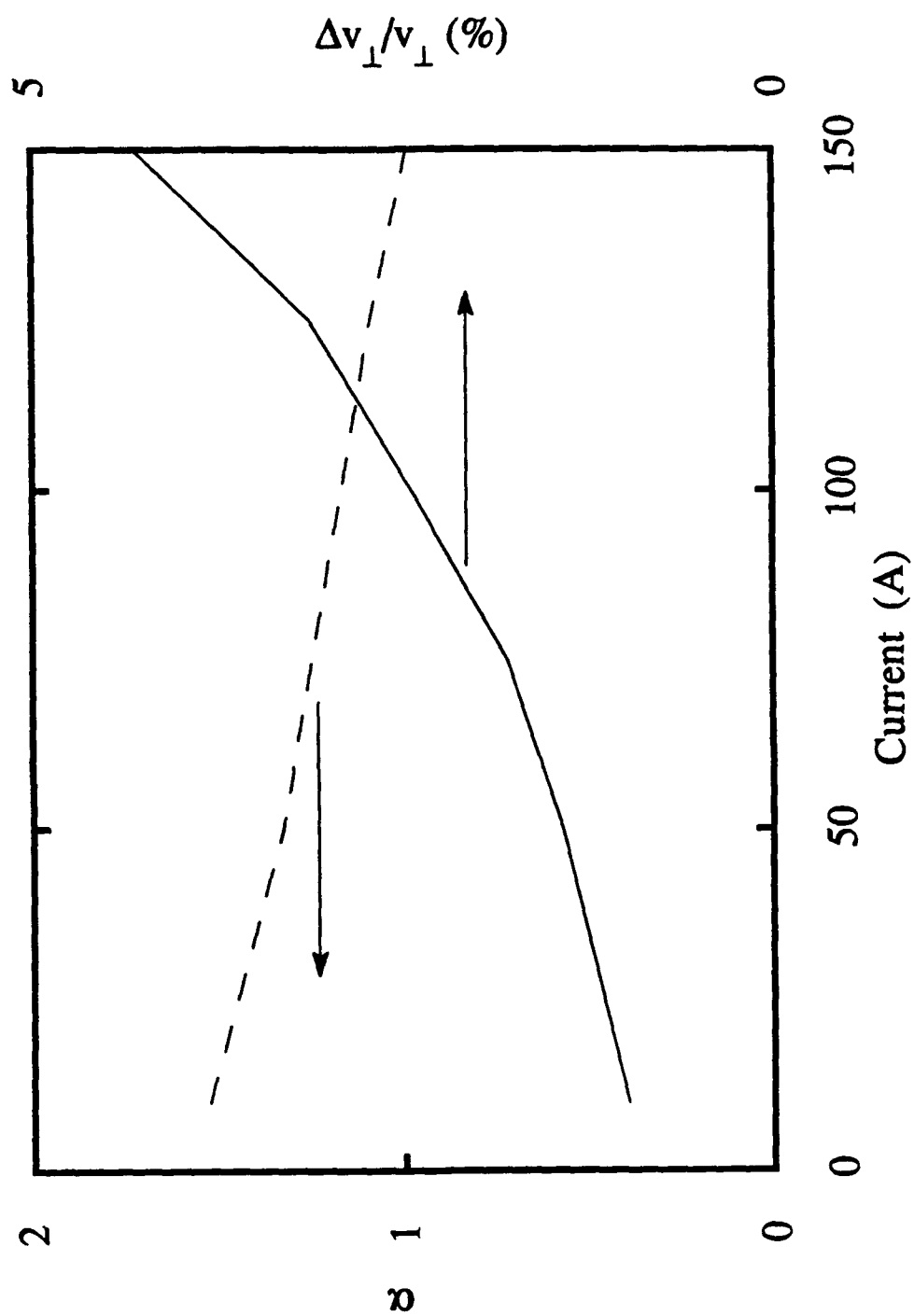


Fig. 8 — Beam alpha and axial velocity spread with the gun operated in the 250 kV quasioptical gyrotron configuration